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Resolving the Effects of Rotation in Early Type Stars

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ABSTRACT

We review the theory of rotating stars, first developed 80 years ago. Predictions include a specific relation between shape and angular velocity and between surface location and effective temperature and effective gravity. Seen at arbitrary orientation rapidly rotating stars will display ellipsoidal shapes and possibly quite asymmetric intensity distributions. The flattening due to rotation has recently been detected at PTI and VLTI. With the increasing baselines available in the visible and the implementation of closure phase measurements at the NPOI it is now possible to search for the surface brightness effects of rotation. Roche theory predicts only large scale deviations from the usual centro-symmetric limb-darkened models, ideal when the stellar disks are only coarsely imaged as now. We report here observations of Altair and Vega with the NPOI using baselines that detect fringes beyond the first Airy zero in both objects. Asymmetric, non-classical intensity distributions are detected. Both objects appear to be rotating at a large fraction of their breakup velocity. Vega is nearly pole on, accounting for its low apparent rotational velocity. Altair's inclination is intermediate, allowing high S/N detection of all the predicted features of a Roche spheroid. We describe how these objects will test this fundamental theory and how Vega's role as a standard will need reinterpretation.

Keywords: interferometry, stars, rotation, gravity darkening

1. INTRODUCTION

Eighty years ago von Zeipel[1] worked out the theory of rotating stars. The theory predicts that such stars will be flattened, adopting the figure of a Roche spheroid. He showed that in radiative equilibrium the energy flux ($\propto T_{eff}^4$) will scale as the effective gravity. The underlying assumptions are that the star is in radiative equilibrium and that it rotates like a solid body.

This theory has proved its worth in close binary systems (where tidal forces mimic centrifugal effects). However, the theory has never been challenged in an isolated, rapidly rotating star. Altair has already been observed with significant flattening at the Palomar Testbed Interferometer,[2] as has Achernar with the VLTI.[3] However, except in the limit of rotation near breakup, flattening is subject to the same $\sin i$ ambiguity as the projected velocity. In particular the flattening seen in Altair is consistent with a $v \sin i \sim 220\,\mathrm{km\,s^{-1}}$, exactly as observed and only broad limits may be set on the tilt, i. The case for Achernar may be stronger, perhaps signaling a breakdown of the simple theory, but the observations need confirmation and even then, whether there is a real breakdown or the theory simply needs extension at the highest rotations, is not clear.

This is about to change. We report here long baseline optical observations of Vega and Altair made with the Navy Prototype Optical Interferometer[4] (hereafter, NPOI). The baselines implemented allow measurements of the visibilities beyond the first zero. A new beam combiner allows closure phase measurements on multiple triangles. Together, these advances allow true, albeit coarse imaging of the surfaces of early-type, rapidly rotating

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stars for the first time. Clear indications of asymmetric brightness distributions are detected which appear to be completely consistent with the von Zeipel theory.

Below, we summarize briefly the main features of Roche spheroids as a description of the figures of rotating stars. We then describe our observations of Altair and Vega *vis-a-vis* the von Zeipel theory. Finally we describe the implications for these two objects and the questions that we will be able to attack in the near future with these measurements.

2. ROCHE SPHEROIDS

The primary approximations in the von Zeipel theory are that the stars are in radiative equilibrium, rotate as solid bodies and that the gravitational field is to first order unaffected by the rotation. The latter can be expected to break down to some extent at high rotation rates.

The rotation is usually expressed as $\omega = \Omega/\Omega_b$, the angular velocity as fraction of the breakup angular velocity. The latter is found by balancing gravity and centrifugal acceleration at the equator, $\Omega_b^2 = GM/R_{eq,b}^3$. This establishes the basic shape of the figure. The scale is usually defined by the polar radius, assumed to be independent of rotation. At breakup $R_p = 2/3R_{eq,b}$. von Zeipel's main result was that $\mathrm{T}_{eff}^4 \propto g_{eff}$, where g_{eff} is the surface gravity less the centrifugal acceleration. Thus, providing the polar values of T_{eff} and g and the two angles describing the viewing geometry, position angle (PA, measured North through East) and tilt (i, where $i = 0$ is pole-on), completes the specification of the model.

To predict intensity distributions we add the assumption that at the surface these objects satisfy the plane-parallel approximation locally and use ATLAS[5] model atmospheres as compiled by Van Hamme[6] to calculate surface brightness. As is well known, the plane-parallel approximation breaks down in the limit of high rotation as the spheroids develop a cusp at the equator. We show in figure 1 the intensity distributions for rotation at $\omega = 0.99$ and 1.0. The development of a cusp is limited to a very small fraction of the stellar surface and only at the very extreme limit of rotational stability. Other limitations of the theory will limit the applicability of this model long before the breakdown of the plane-parallel approximation, at least for stars on or near the Main Sequence.

For this work we have coded a suit of programs to simulate rotationally distorted models in the Roche approximation and have incorporated them as another option in the OYSTER package used for NPOI reductions. Since OYSTER is publicly available, so too is the Roche package.

3. ALTAIR

Altair was the first isolated star detected[2] to have substantial flattening due to rotation and it was added to the NPOI observing queue early on for additional observations. Ohishi[7] was the first to recognize the presence of a large closure phase signal indicating an asymmetric intensity distribution, strongly suggesting a rotation origin.

NPOI data from runs in 2001 and 2002 are available for analysis. Both sets were taken in closure phase mode, the 2002 data involving 6 stations. However, even though the 2001 data involved only three stations, they combined for a significantly longer baseline of about 64 m and we focus on those observations.

The fits are shown in figures 2 and 3 (also see Hummel et al.[8] later in this conference for a preliminary discussion of an improved extraction of the data with coherent integration techniques). A grey-scale representation of the Roche model for Altair is shown in fig 4.

There are still calibration issues with the data that need to be resolved so we give model parameters here as indicative, and do not provide estimates of the errors since the systematics probably dominate, except to say that angles are probably good to a few degrees and the fractional rotation is probably good to a few hundredths. We have assumed a polar temperature of 7800 K, typical of this spectral class. This will probably need upward revision, given the large inclination, but should have little effect on the Roche parameter. A polar surface gravity of $\log g = 4.2$ was assumed.

The derived parameters are $\omega = 0.92$, $i = -69°$, $D_p = 2.94$ mas and $PA = 125°$. These lead to major and minor axes of 3.63 and 3.00 mas. The axis ratio, $D = 0.826$ is a bit smaller than found by PTI[2] which can be

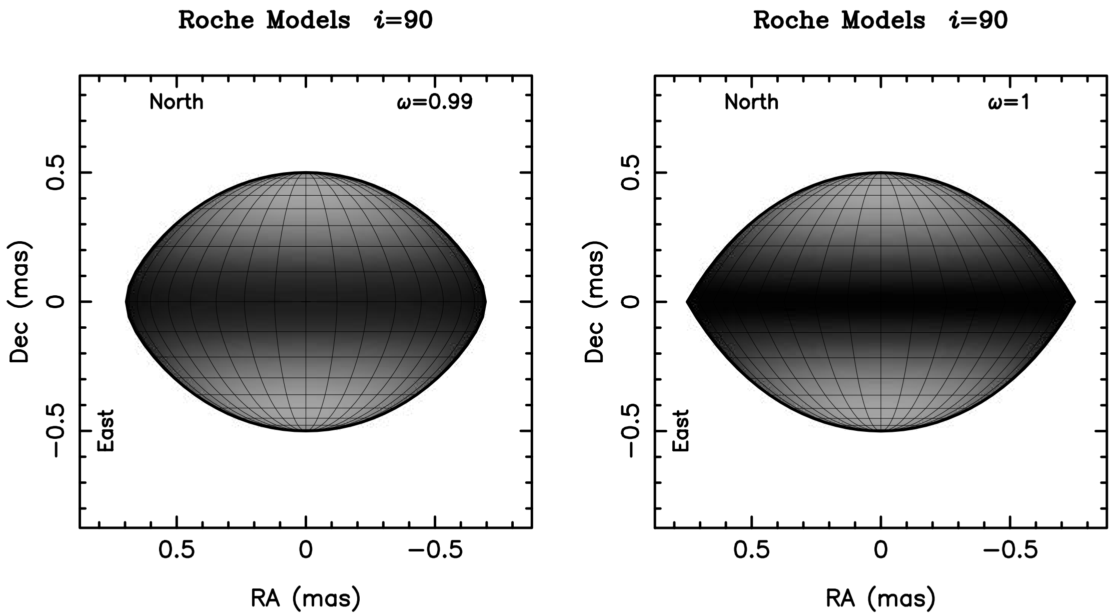

Figure 1. We show Roche spheroids for fractional angular rotations of 0.99 and 1.0 of breakup. The onset of the equatorial cusp is abrupt. For $\omega = 0.99$ the equatorial radius is only 1.39 compared to 1.5 at $\omega = 1$ (in units of the polar axis). The intensity shading is that appropriate to an A0 star at 500 nm, Limb-darkening limits the intensity of the bright poles to about half what would be seen if the poles were viewed from above.

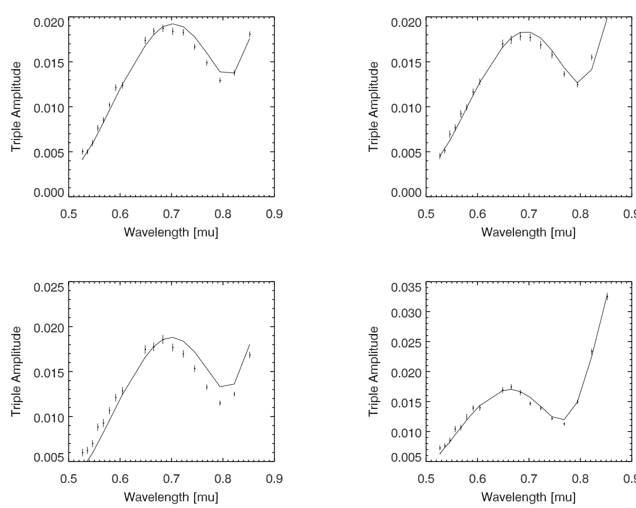

Figure 2. Representative triple amplitudes and a Roche model fit for the May 25, 2001 NPOI run (the triangle used was AE⇒AW⇒W7⇒AE in the NPOI notation). Beyond the first zero the amplitudes reflect the non-classical limb-darkening of the star. Overall the fit is quite good.

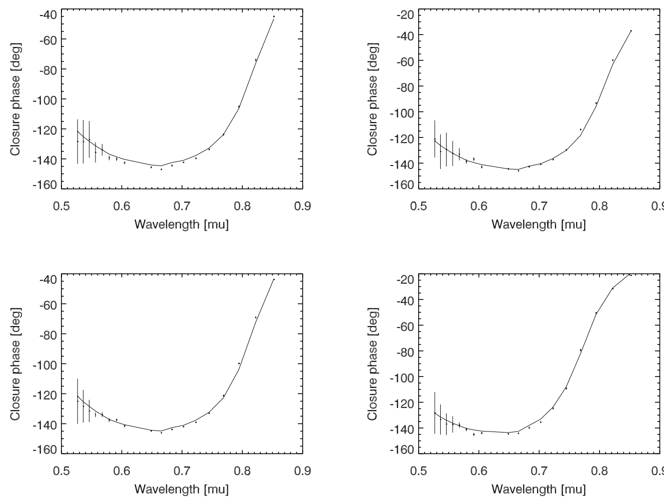

Figure 3. Representative triple (closure) phases and a Roche model fit for the May 25, 2001 NPOI Altair run. A centro-symmetric intensity distribution will yield triple phases of either zero or ($\pm$) 180°, depending on whether the triple amplitude is positive or negative. Here we see the very strong signal of a complex intensity distribution with a large asymmetric component. The Roche model plotted fits these data remarkably well.

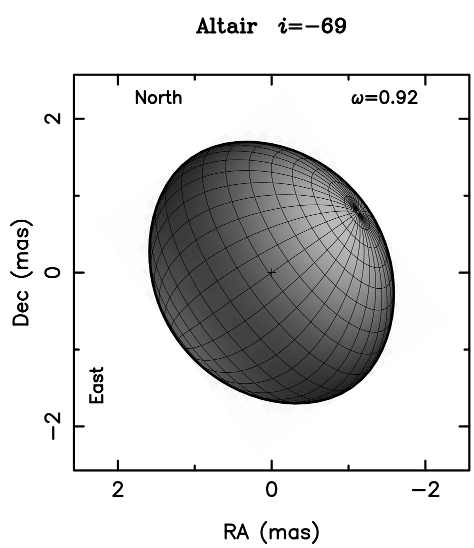

Figure 4. Grey-scale rendering of the Roche model for Altair. See the text for details.

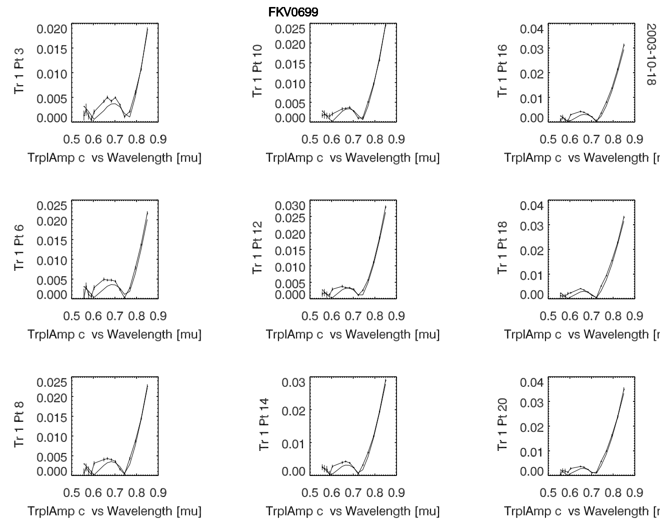

Figure 5. Representative triple amplitudes for triangle AE⇒AC⇒W7⇒AE and a Roche model fit for the Oct 18 2003 NPOI Vega run. Again, amplitudes beyond the first zero reflect the non-classical limb-darkening of the star.

explained by the substantial drop of intensity at the equator. $v \sin i$ is predicted to be $266\,\mathrm{km\,s^{-1}}$ which is a bit higher than measured. However, as has been known for some time[9] the equatorial gravity darkening will lead to a systematic underestimate of the actual rotation. Finally, the model predicts the equator will be fully 1800 K cooler than the pole.

4. VEGA

Vega is a substantially more challenging object to observe. Its brightness creates a number of instrumental problems which we have somewhat moderated by installing aperture stops, reducing the flux by about a factor of 5. This brought signal levels down to about what was experienced with Altair. However, for both objects signal levels are high enough to cause concern about dead time corrections for the detectors. We expect the effects are at the few percent level and are in the process of measuring the coefficients needed.

If that weren't enough, Vega is well known for its sharp lines with recent estimates of $v \sin i = 21\,\mathrm{km\,s^{-1}}$.[10] If the star has some rotation then it is seen nearly pole on, and there has been substantial evidence[10] that this is the case. We thus expect a reduced triple phase signal and that is precisely what is seen.

The observations were obtained in early Fall 2003 during the commissioning phases of the new "6-Way" beam combiner at NPOI. There are a number of calibration issues still being resolved on this instrument, some of which may affect these data. So, as with Altair, we caution that the results here are preliminary and only quote rough errors.

Two independent triangles were used in the measurements which occurred over a period of about a month. By far the best night was Oct 18, 2003 and we discuss those data here. Representative measurements and the model fits are shown in figure 5 for the triple amplitudes and in figure 6 and for the triple phases for the triangle with the longest baseline used (which was a bit shorter than for Altair, about 60 m, further limiting the measurement of the triple phases). Nevertheless, Vega is clearly a pole-on rapid rotator. The key observations are the triple amplitudes. Compared to Altair, where the amplitude of the first fringe is substantially reduced compared to that expected for a uniform disk by the large limb-darkening, Vega's first fringe is almost not detected. This implies extremely heavy limb-darkening, and correspondingly high rotation. The small deviations of the triple phases from "top hat" behavior require both a small tilt and even then rather specific values of the Position Angle. The Roche parameters, which we give below, are reasonably well determined, with the fractional rotation (and in turn the projected diameter which is highly correlated with rotation) probably the more certain.

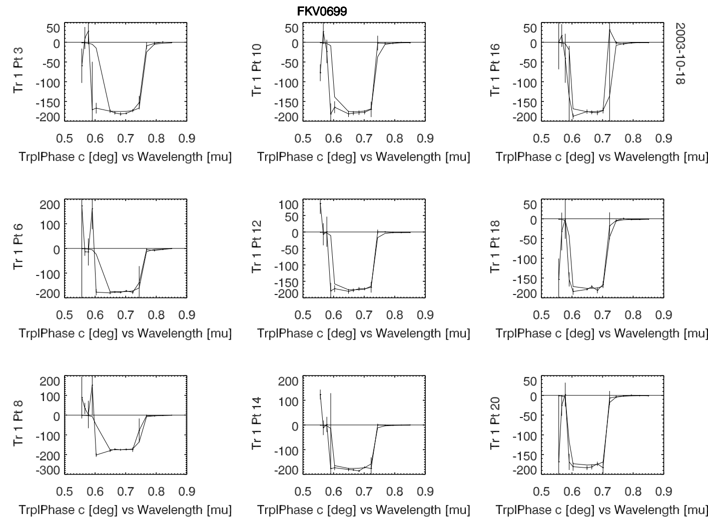

Figure 6. Representative triple phases and a Roche model fit for the October 18, 2003 Vega run, corresponding to the amplitudes shown in figure 5. The triple phases are notable as much because they show such small deviations from "top hat" behavior.

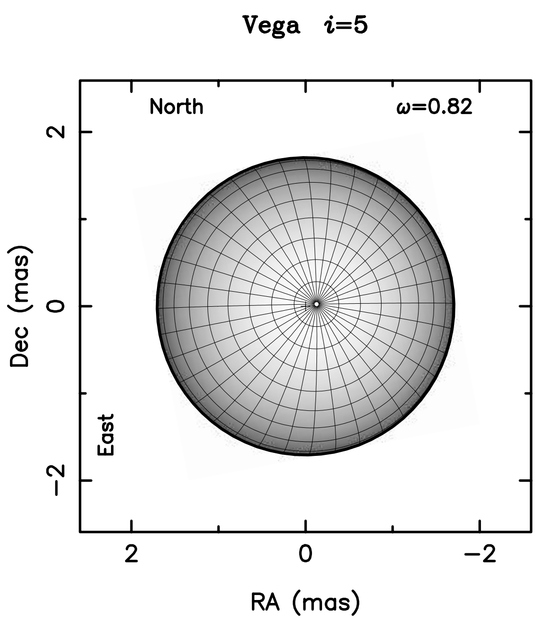

Figure 7. The Roche model for Vega. The cross corresponds to the sub-solar point. The model demonstrates the strong decrease in brightness toward the limb in every direction and the approximate symmetry due to the near pole-on geometry.

Figure 7 shows the Roche model deduced for Vega. We assumed a polar temperature of $T_{eff} = 10000\,\mathrm{K}$ and gravity of $\log g = 4.0$, appropriate for the object. Model fitting produced the following: $\omega = 0.82$, $i = 5°$, $D_p = 2.96\,\mathrm{mas}$ and $PA = 281°$. The derived angular diameters are 3.40 and 3.41 mas along the minor and major axes, respectively. The equatorial temperature is 1500 K cooler than the pole and the predicted $v \sin i = 18\,\mathrm{km\,s^{-1}}$, a little below the measured value of $21\,\mathrm{km\,s^{-1}}$ but certainly in the right neighborhood.

5. PROSPECTS

The identification and initial characterization of the rotation properties of these two objects is a major breakthrough. Each offers the potential of unique insights into a variety of problems. For example, a critical assumption in the application of Roche models is that stars rotate like solid bodies in their radiative zones. Recent advances in helioseismology[11] have shown that the differential rotation in the solar convective envelope undergoes an abrupt transition to solid body rotation where convection ceases. However, early type stars invert that order, with convective cores and radiative envelopes and however unlikely, it may be that the solar experience does not apply. Indeed, one recent explanation[12] for the high degree of flattening for α Eri[3] assumes the angular velocity varies through the interior.

Altair has the potential to resolve this issue with the recent announcement[13] that δ Scuti pulsations have been detected in the object for the first time. Combined with the overall state of the rotation such as we demonstrate here, analysis of the pulsations have the potential to place limits on any variation of the angular rotational rate in the envelope.

The characterization of Vega's rotation will have even deeper ramifications. Probably the most immediate involves its status as the fundamental calibrator for UV-Visible-NearIR observations. For years researchers[14] have reported small but persistent excesses in the absolute fluxes adopted for Vega. Comparisons[15] with other A and B stars showed Vega to be apparently normal, leading to the suggestion that the error was in the model atmospheres. Rapid rotation has the potential to explain this. Model atmosphere fluxes are peaked in frequency. Convolving them with a range of models appropriate of a rotating stellar surface will broaden the frequency distribution. Since the peak of the distribution for A stars is at about 400 nm, one expects rotation to produce infrared excesses.

Vega has also achieved prominence recently[16] as the first and brightest member of the class of stars hosting extensive debris disks. An important parameter in understanding the status of those disks is their age, usually taken as the age of the star which is estimated from the luminosity compared to the zero age main sequence. In the case of a rapid rotator seen pole-on, the apparent luminosity is higher than the actual luminosity which will result in an overestimate of the star's age and thus the evolutionary state of the disk.

Most stars hotter than about F5 rotate rapidly. We are now at the threshold of probing that characteristic in individual stars. This will address old questions and open exciting new areas of research.

6. ACKNOWLEDGMENTS

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